

# Electroweak Baryogenesis in a Supersymmetric $U(1)'$ Model

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We construct an anomaly free supersymmetric  $U(1)'$  model with a secluded  $U(1)'$ -breaking sector. We study the one-loop effective potential at finite temperature, and show that there exists a strong enough first order electroweak phase transition for electroweak baryogenesis (EWBG) because of the large trilinear term  $A_h hSH_d H_u$  in the tree-level Higgs potential. Unlike in the MSSM, the lightest stop can be very heavy. We consider the non-local EWBG mechanism in the thin wall regime, and find that within uncertainties the observed baryon number can be generated from the  $\tau$  lepton contribution, with the secluded sector playing an essential role. The chargino and neutralino contributions and the implications for the  $Z'$  mass and electric dipole moments are briefly discussed. PACS numbers: 12.60.Jv, 12.60.Cn [ UPR-1063-T ]

The baryon asymmetry of the universe has been measured by WMAP [1]. Combining their data with other CMB and large scale structure results, they obtain the ratio of baryon density  $n_B$  to entropy density  $s$

$$n_B/s \sim 8.7^{+0.4}_{-0.3} \times 10^{-11} . \quad (1)$$

To generate the baryon asymmetry, the Sakharov criteria [2] must be satisfied: (1) Baryon number ( $B$ ) violation; (2)  $C$  and  $CP$  violation; (3) A departure from thermal equilibrium. Electroweak (EW) baryogenesis is especially interesting because the Sakharov criteria can be satisfied in the Standard Model (SM) [3]. However, in the SM the electroweak phase transition (EWPT) cannot be strongly first order for the experimentally allowed Higgs mass, and the  $CP$  violation from the CKM matrix is too small. In the Minimal Supersymmetric Standard Model (MSSM), although there are additional sources of  $CP$  violation in the supersymmetry breaking parameters, a strong enough first order EWPT requires that the lightest stop quark mass be smaller than the top quark mass  $\sim 175$  GeV. Also, the mass of the lightest  $CP$  even Higgs must be smaller than 120 GeV, which leaves a small window above the current limit [4]. In the Next to Minimal Supersymmetric Standard Model (NMSSM), a trilinear term  $A_h hSH_d H_u$  in the tree-level Higgs potential may induce a strong enough first order EWPT [5,6], and the effective  $\mu$  parameter is given by  $h\langle S \rangle$  from the Yukawa term  $hSH_d H_u$  in the superpotential in the best-motivated versions. However, most versions either involve a discrete symmetry and serious cosmological domain wall problems [7], or reintroduce the  $\mu$  problem [6].

The possibility of an extra  $U(1)'$  gauge symmetry is well-motivated in superstring constructions [8]. Similar to the NMSSM, an extra  $U(1)'$  can provide an elegant solution to the  $\mu$  problem due to the Yukawa term  $hSH_d H_u$  [9,10]. However, there are no discrete symmetries or domain wall problems. The MSSM upper bound of  $M_Z$  on the tree-level mass of the lightest MSSM Higgs scalar is relaxed, both in models with a  $U(1)'$  and in the

NMSSM, because of the Yukawa term  $hSH_d H_u$  and the  $U(1)'$   $D$ -term [11]. Higgs masses lighter than those allowed by LEP in the MSSM are also possible, with the limits relaxed by mixings between Higgs doublets and singlets. There are stringent limits on an extra  $Z'$  from direct searches during Run I at the Tevatron [12] and from indirect precision tests at the  $Z$ -pole, at LEP 2, and from weak neutral current experiments [13]. In typical models  $M_{Z'} > (500 - 800)$  GeV and the  $Z - Z'$  mixing angle  $\alpha_{Z-Z'}$  is smaller than a few  $\times 10^{-3}$ . (The specific parameters considered here yield a  $Z'$  mass of around 920 GeV, while the exclusion for this case is  $\sim 540$  GeV.) To explain the  $Z - Z'$  mass hierarchy without fine-tuning, two of us with J. Erler proposed a supersymmetric  $U(1)'$  model with a secluded  $U(1)'$ -breaking sector in which the squark and slepton spectra can mimic those of the MSSM, the electroweak symmetry breaking is driven by relatively large  $A$  terms, and a large  $Z'$  mass can be generated by the VEVs of additional SM singlet fields that are charged under the  $U(1)'$  but do not directly contribute to the effective  $\mu$  parameter [14]. Here, we consider EWBG in this model.

The model has one pair of Higgs doublets  $H_u$  and  $H_d$ , and four SM singlets,  $S$ ,  $S_1$ ,  $S_2$ , and  $S_3$  whose  $U(1)'$  charges satisfy

$$Q_S = -Q_{S_1} = -Q_{S_2} = \frac{1}{2}Q_{S_3}, \quad Q_{H_d} + Q_{H_u} + Q_S = 0. \quad (2)$$

The superpotential for the Higgs sector is

$$W_H = hSH_d H_u + \lambda S_1 S_2 S_3, \quad (3)$$

where  $h$  is associated with the effective  $\mu$  term. The off-diagonal nature of  $W_H$  is motivated by string constructions. We also introduce the supersymmetry breaking soft terms

$$\begin{aligned} V_{soft}^H = & m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \sum_{i=1}^3 m_{S_i}^2 |S_i|^2 \\ & - (A_h hSH_d H_u + A_\lambda \lambda S_1 S_2 S_3 + m_{SS_1}^2 S S_1 \\ & + m_{SS_2}^2 S S_2 + m_{S_1 S_2}^2 S_1^\dagger S_2 + \text{H.C.}) . \end{aligned} \quad (4)$$

$m_{SS_1}^2$  and  $m_{SS_2}^2$  are needed to break two unwanted global  $U(1)$  symmetries.  $m_{S_1S_2}^2$  allows the possible tree-level CP violation. There is an almost  $F$  and  $D$  flat direction involving  $S_i$ , with the flatness lifted by  $\lambda$ . For a sufficiently small  $\lambda$ , the  $Z'$  mass can be arbitrarily large [14].

An anomaly-free supersymmetric  $U(1)'$  model can be constructed by embedding  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$  into  $E_6$ . (We are not considering a full  $E_6$  grand unified theory, but only using the  $U(1)'$  charges.) The  $U(1)'$  is a linear combination of  $U(1)_\chi$  and  $U(1)_\psi$ ,

$$Q' = \cos \theta Q_\chi + \sin \theta Q_\psi, \quad (5)$$

where  $U(1)_{\chi,\psi}$  are defined by

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi, \quad (6)$$

and  $\theta$  is a mixing angle. We assume that the orthogonal  $U(1)'$  is absent or very heavy. We assume three  $\mathbf{27}$ s, which include three families of the SM fermions, one pair of Higgs doublets ( $H_u$  and  $H_d$ ), and a number of SM singlets, extra Higgs-like doublets, and other exotics. We assume that the four SM singlets  $S, S_1, S_2, S_3$  are the  $S_L, S_L^*, S_L^*$  and  $\bar{N}^*$ , respectively, in two (partial) pairs of  $\mathbf{27}$  and  $\mathbf{27}^*$  which include the extra  $S_L$  and  $\bar{N}$  to cancel the  $U(1)'$  anomalies. To be consistent with minimal gauge coupling unification, we introduce one pair of vector-like doublets  $H'_u$  and  $\bar{H}'_u$  from a pair of  $\mathbf{27} + \mathbf{27}^*$  [15]. We assume the other particles in the  $\mathbf{27} + \mathbf{27}^*$  pairs are very heavy. From  $Q_S = \frac{1}{2}Q_{S_3}$ , *i.e.*,  $Q_{S_L} = \frac{1}{2}Q_{\bar{N}^*}$ , we obtain  $\tan \theta = \frac{\sqrt{15}}{9}$ . The  $U(1)_\chi, U(1)_\psi$  and  $U(1)'$  charges are given in Table 1. The tiny neutrino masses can be generated, *e.g.*, by the double see-saw or Type II see-saw mechanisms.

Table 1. Decomposition of the  $E_6$  fundamental  $\mathbf{27}$  representation for the left-chiral fields under  $SO(10)$ ,  $SU(5)$ , and the  $U(1)_\chi, U(1)_\psi$  and  $U(1)'$  charges.

| $SO(10)$ | $SU(5)$                       | $2\sqrt{10}Q_\chi$ | $2\sqrt{6}Q_\psi$ | $2\sqrt{15}Q'$ |
|----------|-------------------------------|--------------------|-------------------|----------------|
| 16       | $10 (u, d, \bar{u}, \bar{e})$ | -1                 | 1                 | -1/2           |
|          | $\bar{5} (\bar{d}, \nu, e)$   | 3                  | 1                 | 4              |
|          | $1\bar{N}$                    | -5                 | 1                 | -5             |
| 10       | $5 (D, H'_u)$                 | 2                  | -2                | 1              |
|          | $\bar{5} (\bar{D}, H'_d)$     | -2                 | -2                | -7/2           |
| 1        | $1 S_L$                       | 0                  | 4                 | 5/2            |

To study the electroweak phase transition and baryogenesis, we need the one-loop effective potential at finite temperature. In the 't Hooft-Landau gauge and in the  $\overline{MS}$ -scheme, it is [16]

$$V_e(\phi, T) = V_0(\phi) + V_1(\phi, 0) + \Delta V_1(\phi, T) + \Delta V_d(\phi, T), \quad (7)$$

where  $V_0(\phi)$  is the tree-level potential,  $V_1(\phi, 0)$  and  $\Delta V_1(\phi, T)$  are the one-loop corrections at zero and finite temperatures, and  $\Delta V_d(\phi, T)$  is the multi-loop daisy

correction. The technical and numerical details are given in Ref. [17].

The  $U(1)'$  is broken at a first phase transition around 1 TeV, with the  $S_i$  acquiring large VEVs and  $S$  a much smaller one, and the electroweak symmetry at a second transition at the critical temperature  $T_c$ . We plot the potential versus the vacuum expectation value (VEV)  $v \equiv \sqrt{|\langle H_u^0 \rangle|^2 + |\langle H_d^0 \rangle|^2}$  by connecting the true and false minima for the temperatures near the EWPT in FIG. 1 for a set of typical input parameters given in Table 2. The EWPT occurs at  $T_c = 120$  GeV, with

$$v(T_c)/T_c = 1.31, \quad (8)$$

strong enough for EWBG. The transition is induced by the trilinear term  $A_h h S H_d H_u$ , so, unlike in the MSSM, there is no upper bound on the lightest stop mass.

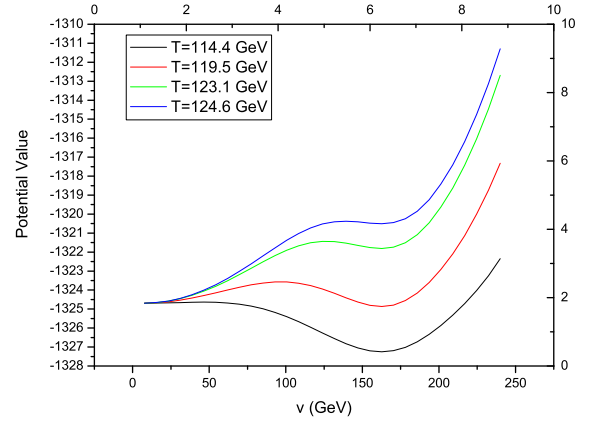


FIG. 1. The potential versus the VEV  $v$  by connecting the true and false minima where  $v \equiv \sqrt{|\langle H_u^0 \rangle|^2 + |\langle H_d^0 \rangle|^2}$ .

Table 2. A set of typical parameters. The energy unit is 72 GeV.

| $h$  | $A_h$         | $\lambda$     | $A_\lambda$ | $m_{SS_1}^2$ | $m_{SS_2}^2$ | $m_{S_1S_2}^2$ |
|------|---------------|---------------|-------------|--------------|--------------|----------------|
| 0.8  | 3.2           | 0.06          | 3.1         | 0.012        | 0.09         | 0.0003         |
| $T$  | $m_{H_d^0}^2$ | $m_{H_u^0}^2$ | $m_S^2$     | $m_{S_1}^2$  | $m_{S_2}^2$  | $m_{S_3}^2$    |
| 1.65 | 0.25          | 0.25          | -0.25       | 0.031        | 0.031        | -0.01          |

The first order EWPT is realized by bubble nucleation. For the non-local EWBG scenario the CP violation is associated with particles interacting in the wall, and  $B$  violation occurs near the wall in the unbroken vacuum. Calculations have been carried out in the thin and thick wall approximations [18,19]. We will assume the thin wall regime which has a relatively simple physical picture. This is justified in our case for the  $\tau$  lepton contribution because the wall thickness  $\delta$  is so small in comparison with the  $\tau$  mean free path. Using the delta function type CP-violation source [17,19], we have

$$\frac{n_B}{s} = -45(1 + \frac{v_w}{\langle v_L \rangle}) \frac{\xi_L m^2 \delta \Delta \theta_{CP} h(\delta, T) \Gamma'_s}{(2\pi)^4 v_w g_* T^4}, \quad (9)$$

where  $m$ ,  $D$ ,  $\langle v_L \rangle$ , and  $\xi_L$  are respectively the fermion mass, diffusion constant, average velocity, and persistence length in the wall frame;  $\Delta \theta_{CP}$  is the  $CP$  phase change of the Higgs field coupling to the fermion;  $\Gamma'_s$  is the sphaleron rate; and  $h(\delta, T) \approx \int_0^T dk_\perp \int_0^{1/\delta} dk_z \frac{k_\perp k_z}{\sqrt{k_\perp^2 + k_z^2}}$  is an integral over momenta for the non-WKB fermions. Up to the leading order contribution for the wall velocity  $v_w$ , Lorentz factors can be neglected in these formulae. Thus, three parameters  $\delta$ ,  $v_w$  and  $\Delta \theta_{CP}$  are the most important physical quantities influencing EWBG.

The bubble wall can be approximated by the stationary solution to the equations of motion for the Higgs fields. Solving these equations analytically is difficult due to the Higgs field multiplicity. However, these field equations are solved for the field configuration for which

$$S_A = \int_{-\infty}^{+\infty} dz [\Sigma_i E_m^i(z)^2 + \Sigma_j E_p^j(z)^2] \equiv 0, \quad (10)$$

where  $E_m^i(z)$  and  $E_p^j(z)$  are the field equations for the magnitude and phase, respectively [20]. We approximate the wall profile and estimate  $\delta$  by applying a kink ansatz to minimize the action  $S_A$ . In our model, the numerical results show that the wall thickness  $\delta$  varies from  $1T^{-1}$  to  $20T^{-1}$  as a monotonically increasing function of these phase changes, and is smaller than the leptons' large mean free path  $\sim (30 - 70)T^{-1}$  [19].

The wall velocity for a newly-born bubble is mainly determined by the effective potential difference, surface tension, and plasma friction. Analytic study is very difficult. Recent numerical work [21] indicates that in the MSSM the wall is extremely non-relativistic and can be as slow as  $v_w \sim 0.01$ . For the  $U(1)'$  model, a systematic study is absent. However, there is a larger wall tension due to the TeV scale  $|S_i|$  and their space varying phases, and an associated larger critical radius (so the shrinking force decreases more slowly). Meanwhile, the plasma friction is larger due to the exotic particles. Thus, the wall velocity is slower than that in the MSSM or NMSSM under the thin wall approximation, and it should be extremely non-relativistic. This fact, together with  $\xi_L > 30T^{-1} \gg \delta$  for left-chiral leptons in our model, make the delta function type CP-violation source a good approximation where no perturbation is generated behind the wall by the injected current [19]. To avoid unnecessary complication, we still take  $\xi_L = 6D\langle v_L \rangle$  as in [19].

Only four combinations of the six phases of the neutral Higgs fields are physical

$$\begin{aligned} \beta_1 &= \theta_S + \theta_{S_1}, \quad \beta_2 = \theta_S + \theta_{S_2}, \\ \beta_3 &= \theta_S + \theta_{H_d^0} + \theta_{H_u^0}, \quad \beta_4 = \theta_{S_1} + \theta_{S_2} + \theta_{S_3}, \end{aligned} \quad (11)$$

where  $\theta_{\phi_i}$  is the phase of  $\phi_i$ . The other two,  $\Sigma_i Q_{\phi_i}^Z \theta_{\phi_i}$  and  $\Sigma_i Q'_{\phi_i} \theta_{\phi_i}$ , where  $Q_{\phi_i}^Z$  and  $Q'_{\phi_i}$  are respectively the

$U(1)_Z$  and  $U(1)'$  charges, are gauge degrees of freedom. There are five complex parameters from the soft terms in Eq. (4):  $A_h h$ ,  $A_\lambda \lambda$ ,  $m_{S_1}^2$ ,  $m_{S_2}^2$  and  $m_{S_1 S_2}^2$ . Only four can be taken as real by field redefinition, and thus, unlike the MSSM, complex VEVs of the Higgs and singlet fields may be induced by an explicitly CP-violating phase  $\gamma$  at tree-level, where  $m_{S_1 S_2}^2 \equiv |m_{S_1 S_2}^2| e^{i\gamma}$ . For the relatively small values we choose for these soft masses, the new contributions to the electric dipole moments (EDMs) of the electron and neutron associated with this sector (from Higgs scalar exchange) are five or six orders smaller than the experimental bounds.

Unlike the MSSM, spontaneous CP breaking (SCPB) can occur at tree-level since a mildly dominant  $m_{S_1 S_2}^2$  soft term will forbid the same values for  $\beta_1$  and  $\beta_2$  for  $\gamma = \pi$ . The SCPB only occurs in the domain wall, and all gauge-independent phases are suppressed to zero in the broken phase, so new contributions to EDMs would vanish entirely. However, bubbles of opposite CP phase and baryon number may be produced, diluting the density. (The explicit CP breaking from the fermion sector avoids problems with cosmological domain walls [22].) We therefore choose  $\gamma \neq \pi$ .

The  $CP$  phase change relevant to baryogenesis is

$$\Delta \theta_{CP} = -\frac{1}{5} \Delta \beta_1 - \frac{1}{5} \Delta \beta_2 + \frac{7}{15} \Delta \beta_3 + \frac{2}{15} \Delta \beta_4. \quad (12)$$

The  $|S_i|$  maintain almost the same large values in both phases, leading to  $\beta_4 = \Delta \beta_4 = 0$ . However,  $|S|$  changes, leading to changes in  $\beta_{1,2,3}$ . We assume a kink ansatz for  $\beta_{1,2}$  through the wall. However,  $\beta_3$  is tricky: from the soft term  $A_h h S H_d^0 H_u^0$ ,  $\beta_3$  is suppressed to zero once  $H_d^0$  and  $H_u^0$  obtain significant VEVs. Due to loops, it is non-zero in the false vacuum, but numerical study shows that the transition to zero occurs in the outer edge of the wall, where  $H_{u,d}^0$  are small. In calculating the asymmetry, we consider the scattered particles by the domain wall as freely propagating with space-dependent mass  $m_\psi(z) = h_\psi \frac{H_d^0(z)}{\sqrt{2}} e^{i\Delta \theta_{H_d^0}(z)}$  for down-type fermions, where  $H_d^0(z)$  is also approximated by a kink function.  $\beta_3$  is therefore nonzero only when  $H_d^0(z)$  is small and is irrelevant. We therefore define an effective CP phase change

$$(\Delta \theta_{CP})_{eff} = -0.2(\Delta \beta_1(z) + \Delta \beta_2(z)). \quad (13)$$

In FIG. 2, we show the  $\gamma$  dependence of the baryon asymmetry for the typical input parameters in Table 2 with  $v_w = 0.01, 0.02$  and  $0.04$ , respectively. We only consider the contributions from the  $\tau$  lepton because the quark diffusion constants and light lepton masses are small. The  $\tau$  lepton contribution is dominated by the left-chiral ones because the  $\tau$  Yukawa coupling is small due to  $\tan \beta \sim 1$  in our model, which implies that the  $\tau$  associated ‘‘decay’’ processes have no time to equilibrate in the right-chiral  $\tau$  lepton diffusion tail [19], hence most

of baryons are directly produced from the rejected left-chiral  $\tau$  leptons. This plot shows that, within theoretical uncertainties, the observed value can be explained from the  $\tau$  lepton contribution alone for  $\gamma$  close to  $\pi$ . These results are rather conservative since we also neglect the contributions from superparticles, such as charginos and neutralinos. As a matter of fact, due to the space-dependent field phases, even if  $\tan\beta$  is a constant during EWPT and the possible damping effects of particles in the bubble wall are also counted in [23], the observed baryon asymmetry can be obtained in our model through the chargino and neutralino contributions if they are lighter than 800 GeV and the stop quarks are not very heavy in comparison with  $T_c$  [17].

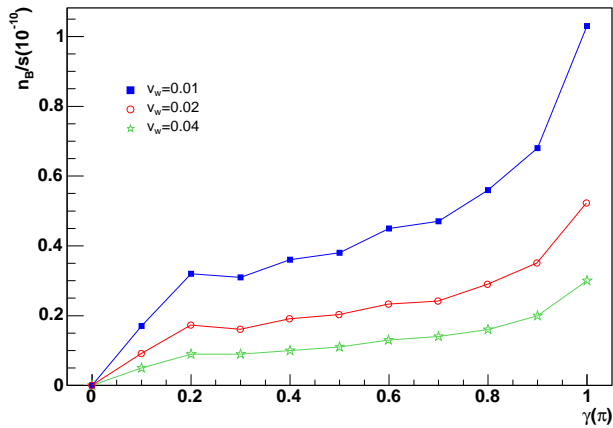


FIG. 2. Baryon asymmetry ( $n_B/s$ ) vs.  $\gamma$ .

There is no baryon number dilution problem for  $\gamma$  slightly smaller than  $\pi$ , because the degenerate vacuum generic in SCPB vanishes. There are degenerate false vacua differing in winding number (i.e., phase changes of  $2\pi$ ). However, these involve a larger phase change with respect to the true vacuum, and their bubble nucleation rate  $\Gamma \sim e^{-\int dx^3 \sum_{i=1}^3 |S_i|^2 (\frac{d\theta_{S_i}}{dx})^2 / T}$  is generally negligible.

In summary, we considered the one-loop effective potential at finite temperature in an anomaly free supersymmetric  $U(1)'$  model with a secluded  $U(1)'$ -breaking sector, and showed that there exists a strong enough first order EWPT for electroweak baryogenesis due to the large trilinear term  $A_h h S H_d H_u$ . We briefly reviewed the non-local electroweak baryogenesis mechanism (in the thin wall regime), and found that within uncertainties the observed baryon number can be generated from the  $\tau$  lepton contribution with the secluded sector playing an essential role.

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